A25

Attenuation of Ischemia/Reperfusion Injury in Rats by a Caspase Inhibitor

Hiroyuki Yaoita, MD; Kazuei Ogawa, MD; Kazuhira Maehara, MD; Yukio Maruyama, MD

Background—Z-Val-Ala-Asp(OMe)-CH_2F (ZVAD-fmk), a tripeptide inhibitor of the caspase interleukin-1β–converting enzyme family of cysteine proteases, may reduce myocardial reperfusion injury in vivo by attenuating cardiomyocyte apoptosis within the ischemic area at risk.

Methods and Results—Sprague-Dawley rats were subjected to a 30-minute coronary occlusion followed by a 24-hour reperfusion. An inert vehicle (dimethylsulfoxide; group 1, n=8) or ZVAD-fmk, at a total dose of 3.3 mg/kg (group 2, n=8), was administered intravenously every 6 hours starting at 30 minutes before coronary occlusion until 24 hours of reperfusion. At this 24-hour point, hemodynamics were assessed by means of cardiac catheterization; then, the rats were killed, and the left ventricle was excised and sliced. The myocardial infarct size/ischemic area at risk and the count of presumed apoptotic cardiomyocytes (terminal deoxynucleotidyl transferase–mediated dUTP-biotin nick end labeling [TUNEL]-positive cells) within the ischemic area at risk were assessed through triphenyltetrazolium chloride staining and TUNEL methods, respectively. Peak positive left ventricular dP/dt was higher ($P=.02$) and left ventricular end-diastolic pressure was lower ($P=.04$) in group 2 than in group 1. The infarct size/ischemic area at risk of group 2 (52.4±4.0%) was smaller ($P=.02$) than that of group 1 (66.6±3.7%), and TUNEL-positive cells were fewer ($P=.0002$) (group 2, 3.1±0.9%; group 1, 11.1±1.0%). Agarose gel electrophoresis revealed DNA laddering in the border zone myocardium of group 1, but DNA ladder formation was attenuated in group 2.

Conclusions—ZVAD-fmk was effective in reducing myocardial reperfusion injury, which could at least be partially attributed to the attenuation of cardiomyocyte apoptosis. (*Circulation.* 1998;97:276-281.)

Key Words: myocardium ■ reperfusion ■ apoptosis ■ caspase

Attempts to reduce the extent of myocardial reperfusion injury have included lowering the risk posed by certain injurious factors and potentiating various aspects of cardioprotection relating to ischemic duration,[1] oxygen free radicals,[2,3] proinflammatory cytokines,[4,5] and preconditioning.[6–10] It has been reported that apoptosis is a significant contributor to myocardial cell death as a result of reperfusion injury.[1] Therefore, it might be hypothesized that this type of injury could be attenuated if a portion of the injured myocardial cells could be rescued from an apoptotic death.

See p 227

The caspase inhibitors, that is, ICE-like protease inhibitors,[11] interfere with apoptosis at a point subsequent to the initiation of the proapoptotic process in cells that have already received apoptosis-promoting signals. As opposed to reducing the exposure of cardiomyocytes to injurious stimuli, apoptosis of these cells is attenuated through modulation of the caspase-related proapoptotic process, and this may allow ischemic myocardium to survive even after receiving significant injury. ZVAD-fmk (fluoro-methylketone), a tripeptide inhibitor of the caspase, is reported to attenuate cardiomyocyte apoptosis in vitro.[6] In the present study, we investigated whether ZVAD-fmk lowers the extent of experimental myocardial reperfusion injury in vivo by attenuating cardiomyocyte apoptosis. In a rat model for myocardial reperfusion injury, infarct size and the appearance of presumed apoptotic cardiomyocytes were assessed in two groups that were or were not administered this protease inhibitor.

Methods

This study was carried out under the supervision of the Animal Research Committee in accordance with the Guideline on Animal Experiments of Fukushima Medical College and Japanese Government Animal Protection and Management Law (No. 105).

Animal Model

Twenty-six of 36 adult male (290 to 310 g body weight) Sprague-Dawley rats were anesthetized through intraperitoneal administration of 30 mg/kg sodium pentobarbital. Under artificial ventilation with a rodent ventilator, a left thoracotomy was performed. The proximal portion of the left coronary artery was surgically occluded for 30 minutes through ligation with a suture (size 6.0) followed by coronary reperfusion through release of the tie. Coronary occlusion was confirmed through elevation of the ST segment on the ECG obtained from a limb lead. Transient ventricular arrhythmias were evoked in all

Received July 21, 1997; revision received October 2, 1997; accepted October 2, 1997.
From the First Department of Internal Medicine, Fukushima Medical College, Hikarigaoka 1, Fukushima 960–12, Japan.
Correspondence to Yukio Maruyama, MD, Professor and Chairman, First Department of Internal Medicine, Fukushima Medical College, Hikarigaoka 1, Fukushima, 960–12, Japan.
E-mail yaoita@cc.fmu.ac.jp

Selected Abbreviations and Acronyms

DMSO = dimethylsulfoxide
ICE = interleukin-1β–converting enzyme
I/R = infarct size/ischemic area at risk
(±)-LV dP/dt = peak positive (+) and negative (−) first derivatives of left ventricular pressure
LVEDP = left ventricular end-diastolic pressure
LVSP = left ventricular peak systolic pressure
PMN = polymorphonuclear leukocyte
TdT = terminal deoxynucleotidyl transferase
TTC = triphenyltetrazolium chloride
TUNEL = terminal deoxynucleotidyl transferase–mediated dUTP-biotin nick end labeling
ZVAD-fmk = Z-Val-Ala-Asp(OMe)-CH_2F

rats ≈5 minutes after coronary occlusion, but these usually disappeared after 10 minutes of occlusion. After coronary reperfusion, the tie was left loose on the surface of the heart, the chest was closed, and the intratracheal tube and ECG electrodes were removed. The rats were returned to their cages, where they awakened, and they were allowed free access to food and water until they were killed 24 hours later.

One milligram of ZVAD-fmk (Enzyme Systems Products) was dissolved in 107 μL of DMSO (Wako Pure Chemicals). In group 2 animals (n=8), ZVAD-fmk, at one fourth of a total dose of 3.3 mg/kg body weight, was administered as a bolus into the tail vein four times during the study (first 30 minutes before coronary occlusion and then three times every 6 hours after reperfusion). The same amount of an inert vehicle (DMSO) was administered in the same manner to rats of group 1 (n=8).

To assess whether the amount of DMSO used as a vehicle would have a toxic effect in vivo, one fourth of a total DMSO volume of 353 μL/kg body weight (n=5) or the same volume of saline (n=5) was administered four times to sham-operated rats in the same manner as to groups 1 and 2.

Leukocytes are known to be involved in the formation of myocardial reperfusion injury.[12] As a positive control for this model of coronary reperfusion injury, 4 rats were administered absorbed polyclonal rabbit anti-rat PMN antisera at a dose of 3 mL/kg (Inter-Cell Technologies) 36 hours before coronary occlusion. Each was subjected to the 30-minute coronary occlusion and 24-hour reperfusion protocol, and 0.5 mL of blood was taken before occlusion and just before death.

Hemodynamic Assessment

Twenty-four hours after coronary reperfusion, rats were anesthetized again through intraperitoneal administration of 30 mg/kg sodium pentobarbital. ECG readings were monitored, and a polyethylene tube (PE 50; Becton-Dickinson) was inserted into the left ventricular cavity via the right carotid artery. LVSP, LVEDP, and (±)-LV dP/dt were measured using a polygraph system (AP601G; Nihon Koden).

Assessment of Infarcted Area and Detection of TUNEL-Positive Cardiomyocytes

After hemodynamics were assessed at 24 hours of coronary reperfusion, 0.5 mL of blood was obtained from the catheter for measurement of blood cells. Then, an intratracheal tube was inserted, and the chest was reopened under artificial ventilation. The coronary artery was again briefly occluded through ligation of the tie that remained at the site of the previous occlusion. Immediately after the ligation, 1% Evans blue solution was infused through the catheter into the beating left ventricular cavity to delineate the ischemic area at risk (underperfused and then reperfused area) of the left ventricle. After administration of an excessive dose of sodium pentobarbital into the left ventricular cavity, the heart was excised and cross-sectioned from the apex to the atrioventricular groove into five specimens of ≈2 mm in thickness with the use of a stereoscope. Because there may be some anatomic differences in the left coronary artery of each rat, the three middle slices were prepared for morphometry to determine the ischemic area at risk. These slices were incubated with a 4% TTC[13] solution for 30 minutes at 37°C in a dark room. Then, ischemic but viable (TTC-stained) and infarcted (TTC-unstained) zones within the underperfused and then reperfused area (Evans blue–unstained) and the nonischemic area (Evans blue–stained) were stereoscopically measured using the point-counting method of Weibel[14] with an eyepiece equipped with a 25-square grid (Integration No. 1; Zweiss) under 100× magnification, and I/R was calculated. These slices were then fixed in 10% neutral-buffered formalin. Using paraffin sections that were 4 μm thick, TUNEL was performed as described previously[15] with minor modifications. Briefly, nuclei of tissue sections were stripped of proteins through incubation with 20 μg/mL proteinase K (Sigma Chemical) for 15 minutes at room temperature. The slides were incubated with 2% H_2O_2 for 5 minutes to allow inactivation of endogenous peroxidase and then incubated for 60 minutes at 37°C with 0.3 EU/μL TdT (Takara Schuzo Co) and 0.04 nmol/μL biotinylated dUTP (Boehringer-Mannheim Biochemica) in TdT buffer containing 30 mmol/L Tris-HCl, pH 7.2, 140 mmol/L sodium cacodylate, and 1 mmol/L cobalt chloride. The reaction was terminated with buffer containing 300 mmol/L NaCl and 30 mmol/L sodium citrate. The slides were coated with avidin-conjugated peroxidase (Medical and Biological Laboratories) diluted 1:3000 in PBS and visualized with the use of chromogen 3,3′-diaminobenzidine (Dojindo) and H_2O_2. Counterstaining was performed with 2% methyl green. Using this method, each cardiomyocyte could be defined, and TdT-positive or -negative nuclei were stained dark brown or light green, respectively, under light microscopy. When the TUNEL method was performed, positive controls were always included. For DNase treatment in situ,[15] sections were processed with proteinase K, and peroxidase inactivation was carried out as described above. Next, the sections were pretreated with DN buffer (30 mmol/L Tris-HCl, pH 7.2, 140 mmol/L K cacodylate, 4 mmol/L $MgCl_2$, and 0.1 mmol/L dithiothreitol); then, DNase I (Sigma) at 100 ng/mL was dissolved in this buffer and used to cover each section. After a 15-minute incubation at room temperature, the slides were washed extensively with double-distilled water, and DNA nick end labeling was carried out.

Using an eyepiece for the point-counting method (Integration No. 1, Zweiss), which was performed under a light microscope at a magnification of 400×, we determined the count ratio of the area of cardiomyocytes with TdT-stained nuclei with that of total cardiomyocytes (TUNEL-positive cardiomyocytes) within the ischemic area at risk. The entire area was searched through an orderly shifting of the visual field using the outer grids of the eyepiece for orientation. TUNEL-positive cardiomyocytes were carefully distinguished from TUNEL-positive noncardiomyocytes, such as macrophages.

To assess the distribution of the infarcted area and TUNEL-positive cardiomyocytes in the left ventricular wall, we subdivided the ischemic area at risk into three transmural stratified layers of equal thickness (epicardial, middle, and endocardial) in each slice mentioned above (Fig 1). We also divided the ischemic area at risk into five radial segments, and then these five radial segments were rearranged as (Fig 1) a right lateral border segment adjacent to the interventricular septum; a total of three central segments; and a left lateral border segment adjacent to the left ventricular posterior wall. For each of the segments or layers, I/R and TUNEL-positive cardiomyocytes were calculated, as well as for the entire ischemic area at risk.

Using some of the paraffin sections of groups 1 and 2, hematoxylin and eosin staining was also performed for confirmation of myocardial reperfusion injury, such as myocardial cell coagulation, contraction bands, bleeding, and inflammatory cell infiltration.

Genomic DNA Extraction and Agarose Gel Electrophoresis

Rats subjected to the same occlusion and reperfusion protocol as groups 1 and 2, respectively (n=3 each group), had their hearts excised at 24 hours after reperfusion, and underperfused myocardium was delineated using Evans blue. The excised heart was sliced immediately as described above. Because TUNEL-positive cardio-

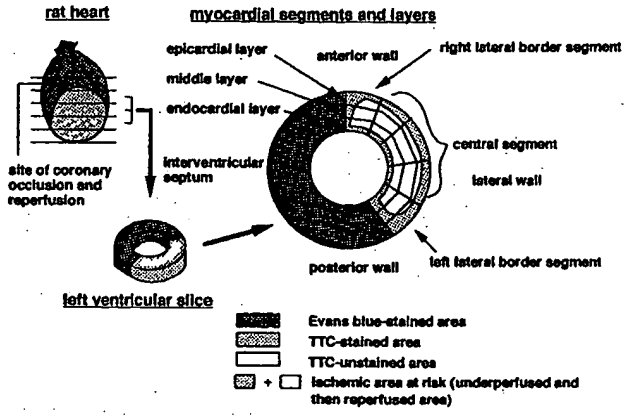

Figure 1. Myocardial segments and layers for assessment of distribution of the infarcted area and TUNEL-positive cardiomyocytes. The three middle slices of the five left ventricular slices of each heart were analyzed for measurements of the infarcted area and TUNEL-positive cardiomyocytes. The entire ischemic area at risk was first divided into five radial segments and then classified into three segments (right lateral border, central three radial segments, and left lateral border segment). The ischemic area at risk (R) was also divided into three myocardial layers (endocardial, middle, and epicardial layers). The measurements of I/R and TUNEL-positive cardiomyocytes were done in the entire ischemic area at risk, as well as in each ischemic portion.

myocytes were found mainly in the lateral border zones and the endocardial side of the ischemic area at risk (as noted in "Results"), we isolated fresh myocardial specimens from these zones and from the core of infarcted zones (mainly corresponding to the zone of the central segment, including middle and epicardial layers in Fig 1) for DNA extraction. Each myocardial specimen weighed ≈0.2 mg and was minced in homogenization buffer (10 mmol/L Tris-HCl, 150 mmol/L NaCl, and 10 mmol/L EDTA, pH 8.0) at 0°C and homogenized for 15 seconds at 10 000 rpm using a Polytron homogenizer (Kinematica AG). The homogenate was then treated with 100 μg/mL proteinase K and 0.1% SDS for 90 minutes at 50°C. The DNA was extracted with phenol and chloroform followed by ethanol precipitation. The pellet was resuspended in TE buffer (10 mmol/L Tris-HCl, pH 8.0, and 1 mmol/L EDTA) and treated with DNase-free RNase (Boehringer-Mannheim) for 2 hours at 37°C. The concentration of DNA was measured through spectrophotometry, and 10 μg of each DNA sample was then electrophoretically fractionated on a 1.5% agarose gel containing ethidium bromide at a concentration of 0.4 μg/mL. DNA was visualized with a UV (302 nm) transilluminator, and the gel was photographed with the use of a Polaroid camera.

Statistical Analysis

Data are expressed as mean±SEM. To compare group 1 (control ischemia/reperfusion) with group 2 or to compare the two groups of sham-operated rats, an unpaired *t* test was performed. For comparisons between the positive anti-PMN control and the other groups, one-way ANOVA followed by Fisher's posthoc comparison was carried out. For comparisons in I/R and TUNEL-positive cardiomyocytes among different myocardial portions, two-way ANOVA followed by Fisher's posthoc comparison was carried out. A value of $P<.05$ was considered statistically significant.

Results

Hemograms

White blood cell counts just before death revealed no difference between group 1 (9502±351/μL) and group 2 (9350±435/μL). In anti-PMN–treated rats, white blood cell counts were 956±132/μL ($P<.0001$ versus group 1 and group 2) before coronary occlusion and 1081±156/μL ($P<.0001$ versus group 1 and group 2) just before death. In this positive control group, lymphocytes made up most of the white blood cells (>99%).

Positive Control for the Rat Model of Reperfusion Injury

The ischemic area at risk was 53.0±2.5% (NS versus group 1 and group 2), and the I/R was 51.0±1.7% ($P<.05$ versus group 1, NS versus group 2).

Hemodynamics

Although the LVSP did not differ between groups 1 and 2, the LVEDP of group 2 was lower ($P=.04$) than that of group 1 (Table). The positive LV dP/dt of group 2 was greater ($P=.02$) than that of group 1, but the heart rates of the two groups did not differ.

For the sham-operated rats, administration of DMSO or saline resulted in no differences in LVSP/EDP or LV dP/dt value or in the heart rate.

Myocardial Infarct Size and TUNEL-Positive Cardiomyocytes

The ischemic areas at risk of groups 1 and 2 were similar (53.9±2.9% in group 1 and 55.4±3.0% in group 2, NS). In the entire ischemic area at risk, the I/R of group 2 (52.4±4.0%) was significantly ($P=.02$) smaller than that of group 1 (66.6±3.7%) (Fig 2, left). The I/Rs of left and right lateral border segments or endocardial and epicardial layers were smaller ($P<.05$, $<.05$, or $P<.05$, $<.01$, respectively) than that of the central segment or that of the middle layer in group 1 (Fig 3). In group 2, the I/Rs of all of three myocardial segments and all of three layers were smaller ($P<.05$, each) than those of group 1.

We confirmed that all nuclei of cardiomyocytes on sections subjected to DNase treatment (as a positive control for the TUNEL

Hemodynamics Before Death

Group	LVSP/LVEDP, mm Hg	LV dP/dt, mm Hg/s	Heart Rate, bpm
1	133±5/9±1	+4296±204/−4385±337	428±18
2	136±8/5±1*	+4907±129*/−4715±227	409±14
PMN-depleted (positive controls)	126±1/6±1	+4716±143/−4684±130	410±10
Sham with DMSO	139±5/2±1†	+5545±205†/−5468±131†	390±10
Sham with saline	137±2/2±1†	+5440±147†/−5088±316	398±14

*$P<.05$, †$P<.01$ vs group 1.
In group 2, LVEDP was lower and +LV dP/dt was higher than in group 1.

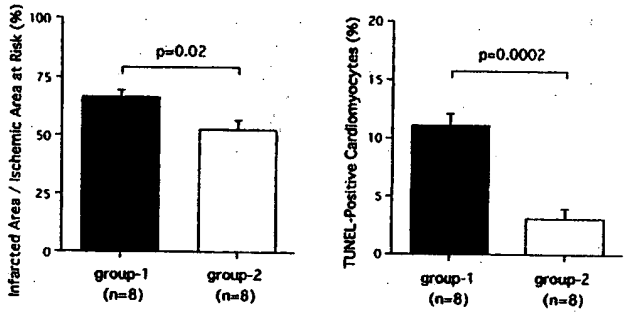

Figure 2. Infarct size and TUNEL-positive cardiomyocytes in the entire underperfused and then reperfused area. Left, I/R. Right, TUNEL-positive cardiomyocytes in the ischemic area at risk. The column representing the infarcted area was lower (P=.02) for group 2 than for group 1. The counts of TUNEL-positive cardiomyocytes in group 2 were lower (P=.0002) than in group 1. Group 1, infarcted rats (n=8) administered vehicle; group 2, infarcted rats (n=8) treated with ZVAD-fmk at a total dose of 3.3 mg/kg.

method) were stained dark brown each time the TUNEL method was performed. The concentration of the TUNEL-positive cardiomyocytes of group 2 (3.1±0.9%) was significantly (P=.0002) less than that of group 1 (11.1±1.0%) (Fig 2, right). In group 1, TUNEL-positive cardiomyocytes were greater in left and right lateral segments (P<.05, <.01, respectively) than in the central segment and greater in the endocardial layer (P<.01) but smaller in the epicardial layer (P<.01) than in the middle layer (Fig 4). In group 2, TUNEL-positive cardiomyocytes of all of three segments (P<.01, each) and of endocardial, middle, and epicardial layers (P<.01, <.01, <.05, respectively) were smaller than those of group 1 (Figs 4 and 5). Therefore, there were no significant differences of TUNEL-positive cardiomyocytes in group 2 among the three myocardial segments or three myocardial layers (Fig 4).

Neither TTC-negative zones nor TUNEL-positive cardiomyocytes were detected in the sham-operated rats administered DMSO or saline.

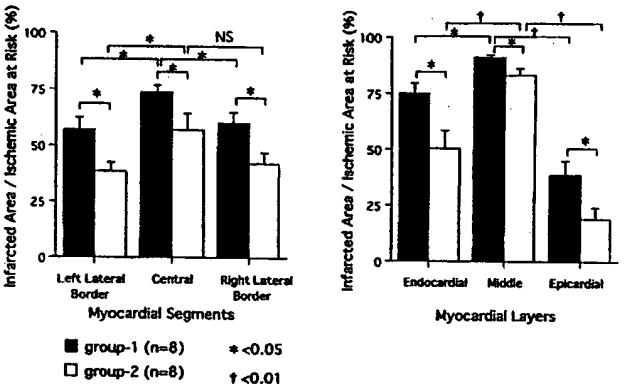

Figure 3. The I/R in myocardial segments or myocardial layers. In group 1, the I/R was smaller in left and right lateral border segments (P<.05, respectively) than the central segment (left). Furthermore, in this group, the I/R was smaller in endocardial and epicardial layers (P<.05, <.01, respectively) than the middle layer (right). In group 2, the I/R of three myocardial segments (left) and of three myocardial layers (right) was smaller than that of the corresponding segments or layers of group 1 (P<.05, respectively).

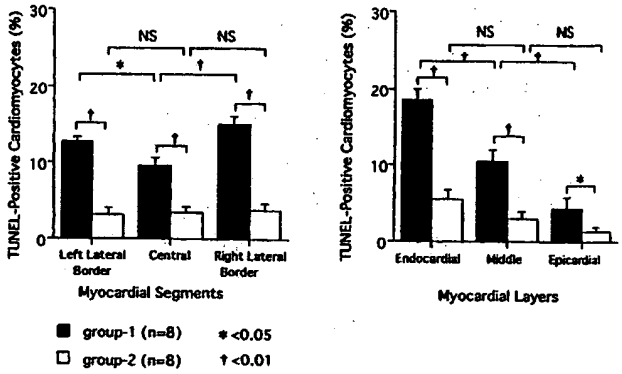

Figure 4. The TUNEL-positive cardiomyocytes in myocardial segments or myocardial layers within the ischemic area at risk. In group 1, TUNEL-positive cardiomyocytes of left and right lateral border segments (left) were greater than that of the central segment (P<.05, <.01, respectively). In this group, TUNEL-positive cardiomyocytes of the endocardial layer or those of the epicardial layer were greater (P<.01) or smaller (P<.01) than those of the middle layer, respectively (right). In group 2, TUNEL-positive cardiomyocytes were smaller than those of group 1 in all of three myocardial segments and three myocardial layers (P<.05 or <.01).

Agarose Gel Electrophoresis

DNA laddering indicative of fragmented DNA was clearly demonstrated in myocardial specimens sampled from the lateral border zones and the endocardial side of the ischemic area at risk in group 1 (lane 4) but was attenuated in group 2 (lane 3), as shown in Fig 6. DNA laddering in the core of infarction was attenuated in group 1 (lane 2) and was absent in group 2 (lane 1).

Discussion

The present study revealed that administration of ZVAD-fmk reduced both the size of the myocardial infarct, as assessed through TTC staining, and the number of TUNEL-positive cardiomyocytes, with significant hemodynamic improvement in vivo in rats that underwent the 30-minute coronary occlusion and 24-hour reperfusion procedure. TUNEL-positive cardiomyocytes appeared to be apoptotic in this study because well-defined (group 1) or attenuated (group 2) DNA laddering on electrophoresis was consistent with a higher or lower value of TUNEL-positive cardiomyocytes, respectively, in the ischemic area at risk of the two groups. In a preliminary study using frozen sections, we confirmed that none of the TUNEL-positive cardiomyocytes were stained with TTC. Therefore, a reduction in their number appeared to contribute to a reduction in the myocardial infarct size. These results suggested that ZVAD-fmk was effective in reducing myocardial reperfusion injury, which could be at least partially attributed to the attenuation of cardiomyocyte apoptosis.

ZVAD-fmk achieved ≈21% decrease in the I/R and ≈72% decrease in TUNEL-positive cardiomyocytes, as ratios compared with the control ischemia/reperfusion. However, the absolute value for decrease in TTC unstained area (≈14%) appeared somewhat greater than that of TUNEL-positive cardiomyocytes (≈8%) (Fig 2); we must be careful to simply compare the absolute values of TUNEL-positive cardiomyocytes with the I/R because the methodology for quantification

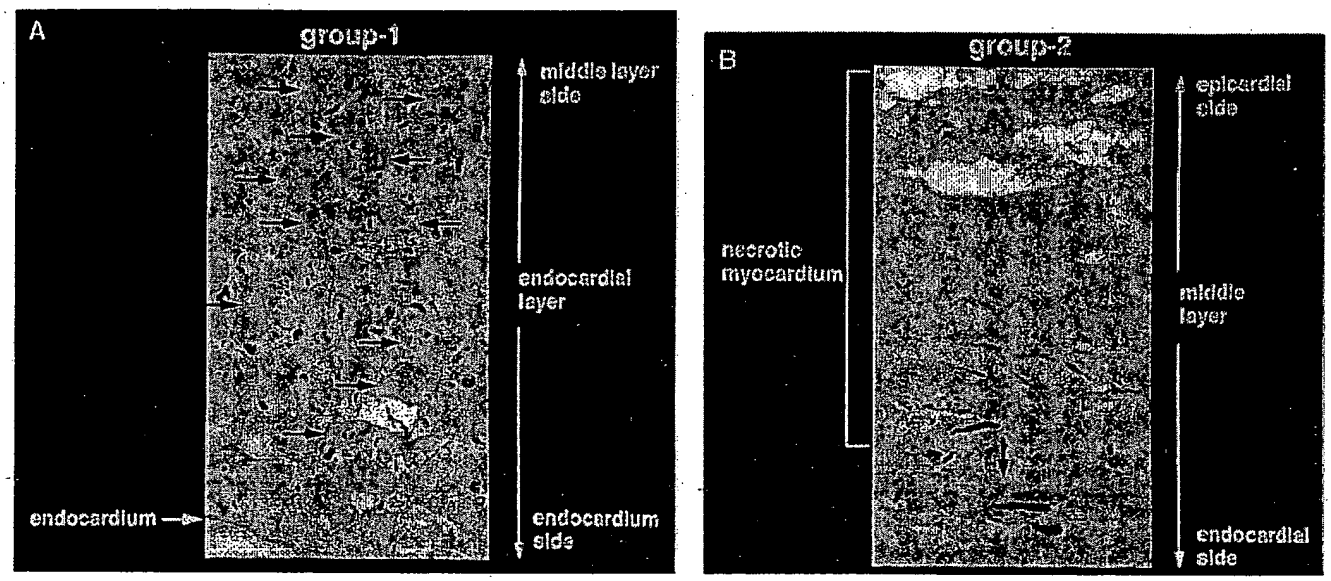

Figure 5. Light microscopic findings on the distribution of TUNEL-positive cardiomyocytes at 24 hours after reperfusion. A, TUNEL-positive cardiomyocytes (arrows) in the endocardial layer of ischemic area at risk on the section from group 1 at a high magnification. B, Possibly necrotic cardiomyocytes (top to middle) and a TUNEL-positive cardiomyocyte (bottom) in the middle layer on the section from group 2. TUNEL-positive cardiomyocytes were frequently detected in the endocardial layer in group 1 (control ischemia/reperfusion) (A). In this group, TUNEL-positive cardiomyocytes were widely spread close to endocardium. In contrast, only a few TUNEL-positive cardiomyocytes were detected mainly in the endocardial side close to the core of infarction in group 2 (ischemia/reperfusion with administration of ZVAD-fmk). The core of infarction consisted of possibly necrotic cardiomyocytes with appearance of disappeared nuclei and degenerated cytoplasm (B). TUNEL-positive cardiomyocytes did not coexist with the mass of these degenerated cardiomyocytes but were present in the surrounding area within central segments or middle layers.

was not the same between TTC staining (histochemical area measurement on myocardial slices) and the TUNEL method (histological cell counting on paraffin sections). Furthermore, we cannot exclude the possibility that ZVAD-fmk interferes with myocardial necrotic process as well as the apoptotic process.[16–18] Tsujimoto and colleagues[17,18] recently revealed that ICE inhibitors retarded necrotic cell death as well as apoptotic cell death in their in vitro system of chemical hypoxia. The authors speculated that there was possible involvement of common mediators in apoptotic and necrotic signal transductions, although their detailed mechanisms remain to be determined. In the present study, we might have observed effects of ZVAD-fmk on these possible but undetermined common mediators. However, our examination in an in vivo system is not suited for approach to signal transductions of these two forms of cell death. The third possibility is the difference in time from initiation of cellular change until elimination between apoptosis and other types of cell death, both forming the infarction. Apoptotic cells are eliminated through phagocytosis in a few minutes in an in vitro condition[19] and in a few hours in an in vivo condition.[20] In contrast, necrotic cardiomyocytes are eliminated much slowly by infiltrating inflammatory cells. Although a turnover of apoptotic cardiomyocytes in vivo has not been clarified so far, it may be speculated that the amount of TUNEL-positive cells quantified at a death stage may not equal the total amount of apoptotic cardiomyocytes that appear during a 24-hour reperfusion period.

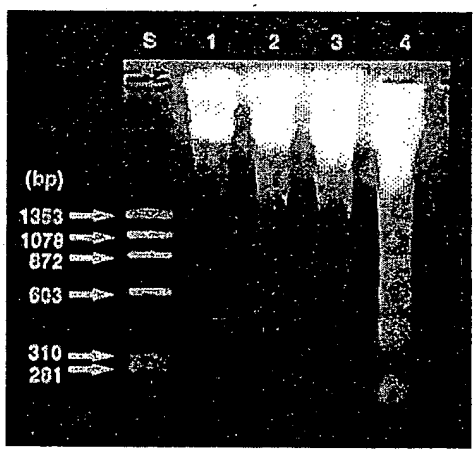

Figure 6. Agarose gel electrophoresis. S indicates size marker (bp). Lane 1, sampled from the core of infarction in myocardium with the same experimental protocol as group 2; lane 2, sampled from the core of infarction in myocardium with the same experimental protocol as group 1; lane 3, sampled from endocardial and lateral border zones of the ischemic area at risk in myocardium with the same experimental protocol as group 2; and lane 4, sampled from endocardial and lateral border zones of the ischemic area at risk in myocardium with the same experimental protocol as group 1. DNA laddering was well defined in the sample from peripheral zone of the ischemic area at risk in control ischemia/reperfusion (lane 4), but DNA ladder formation was attenuated in peripheral zone of the ischemic area at risk in the ZVAD-fmk–treated ischemia/reperfusion (lane 3) or in the core of infarction in control ischemia/reperfusion (lane 2). DNA ladder was not detected in the core of infarction in ZVAD-fmk–treated ischemia/reperfusion (lane 1).

To date, nothing is known about the fate of cardiomyocytes that have been exposed to ZVAD-fmk but have not undergone a proapoptotic process, such as initiation of apoptotic signal transduction via TNF receptor. These cardiomyocytes may continue to survive or may undergo an early death because of injury already sustained. Myocardial infarct size was assessed only at 24 hours after reperfusion in the present study. Future studies will be needed to evaluate the viability of cardiomyocytes that escape apoptosis through assessment of infarct extension in the later phase of reperfusion.

References

1. Fliss H, Gattinger D. Apoptosis in ischemic and reperfused rat myocardium. *Circ Res.* 1996;79:949–956.
2. Ambrosio G, Flaherty JT, Duilio C, Tritto I, Santoro G, Elia PP, Condorelli M, Chiariello M. Oxygen radicals generated at reflow induce peroxidation of membrane lipids in reperfused hearts. *J Clin Invest.* 1991; 87:2056–2066.
3. Bolli R, Zughaib M, Li XY, Tang XL, Sun JZ, Triana JF, McCay PB. Recurrent ischemia in the canine heart causes recurrent bursts of free radical production that have a cumulative effect on contractile function: a pathophysiological basis for chronic myocardial 'stunning.' *J Clin Invest.* 1995;96:1066–1084.
4. Kukielka GL, Smith CW, Manning AM, Youker KA, Michael LH, Entman ML. Induction of interleukin-6 synthesis in the myocardium: potential role in postreperfusion inflammatory injury. *Circulation.* 1995;92: 1866–1875.
5. Krown KA, Page MT, Nguyen C, Zechner D, Gutierrez V, Comstock KL, Glembotski CC, Quintana PJ, Sabbadini RA. Tumor necrosis factor alpha-induced apoptosis in cardiac myocytes: involvement of the sphingolipid signaling cascade in cardiac cell death. *J Clin Invest.* 1996;98: 2854–2865.
6. Gottlieb RA, Gruol DL, Zhu JY, Engler RL. Preconditioning rabbit cardiomyocytes: role of pH, vacuolar proton ATPase, and apoptosis. *J Clin Invest.* 1996;97:2391–2398.
7. Przyklenk K, Zhao L, Kloner RA, Elliott GT. Cardioprotection with ischemic preconditioning and MLA: role of adenosine-regulating enzymes? *Am J Physiol.* 1996;271:H1004–1014.
8. Woolfson RG, Patel VC, Neild GH, Yellon DM. Inhibition of nitric oxide synthesis reduces infarct size by an adenosine-dependent mechanism. *Circulation.* 1995;91:1545–1551.
9. Yao Z, Gross GJ. A comparison of adenosine-induced cardioprotection and ischemic preconditioning in dogs: efficacy, time course, and role of KATP channels. *Circulation.* 1994;89:1229–1236.
10. Homeister JW, Hoff PT, Fletcher DD, Lucchesi BR. Combined adenosine and lidocaine administration limits myocardial reperfusion injury. *Circulation.* 1990;82:595–608.
11. Tatsuta T, Cheng J, Mountz JD. Intracellular IL-1 beta is an inhibitor of Fas-mediated apoptosis. *J Immunol.* 1996;157:3949–3957.
12. Romson JL, Hook BG, Kunkel SL, Abrams GD, Schork MA, Lucchesi BR. Reduction of the extent of ischemic myocardial injury by neutrophil depletion in the dog. *Circulation.* 1983;67:1016–1023.
13. Vivaldi MT, Kloner RA, Schoen FJ. Triphenyltetrazolium staining of irreversible ischemic injury following coronary occlusion in rats. *Am J Pathol.* 1985;121:522–530.
14. Weibel ER. Principles and methods for the morphometric study of the lung and other organs. *Lab Invest.* 1963;12:131–155.
15. Gavrieli Y, Sherman Y, Ben-Sasson SA. Identification of programmed cell death in situ via specific labeling of nuclear DNA fragmentation. *J Cell Biol.* 1992;119:493–501.
16. Shimizu S, Eguchi Y, Kamiike W, Waguri S, Uchiyama Y, Matsuda H, Tsujimoto Y. Bcl-2 expression prevents activation of the ICE protease cascade. *Oncogene.* 1996;12:2251–2257.
17. Shimizu S, Eguchi Y, Kamiike W, Waguri S, Uchiyama Y, Matsuda H, Tsujimoto Y. Retardation of chemical hypoxia-induced necrotic cell death by Bcl-2 and ICE inhibitors: possible involvement of common mediators in apoptotic and necrotic signal transductions. *Oncogene.* 1996;12: 2045–2050.
18. Shimizu S, Eguchi Y, Kamiike W, Waguri S, Uchiyama Y, Matsuda H, Tsujimoto Y. Bcl-2 blocks loss of mitochondrial membrane potential while ICE inhibitors act at a different step during inhibition of death induced by respiratory chain inhibitors. *Oncogene.* 1996;13:21–29.
19. Russell SW, Rosenau W, Lee JC. Cytolysis induced by human lymphotoxin. *Am J Pathol.* 1972;69:103–111.
20. Perlman H, Maillard L, Krasinski K, Walsh K. Evidence for the rapid onset of apoptosis in medial smooth muscle cells after balloon injury. *Circulation.* 1997;95:981–987.